Enhancement of helium exhaust by resonant magnetic perturbations

Oliver Schmitz[1], A. Bader[1], K. Ida[2], M. Kobayashi[2], S. Brezinsek[3], T.E. Evans[4], H. Funaba[2], M. Goto[2], C.C. Hegna[1], O. Mitarai[5], T. Morisaki[2], G. Motojima[2], Y. Narushima[2], D. Nicolai[3], H. Tanaka[2], M. Yoshinuma[2], Y. Xu[6] and the TEXTOR and LHD experiment teams

1 – University of Wisconsin – Madison, Department of Engineering Physics, Madison, WI, USA

2 – National Institute for Fusion Science, High Density Plasma Physics Research Division, Toki, Japan

3 – Forschungszentrum Juelich GmbH, IEC-4, Juelich, Germany

4 – General Atomics, La Jolla, CA, USA

5 – Liberal Arts Education Center, Kumamoto Campus, Takai University, Toruku, Japan

6 – Southwestern Institute of Physics, Chengdu Sichuan, China

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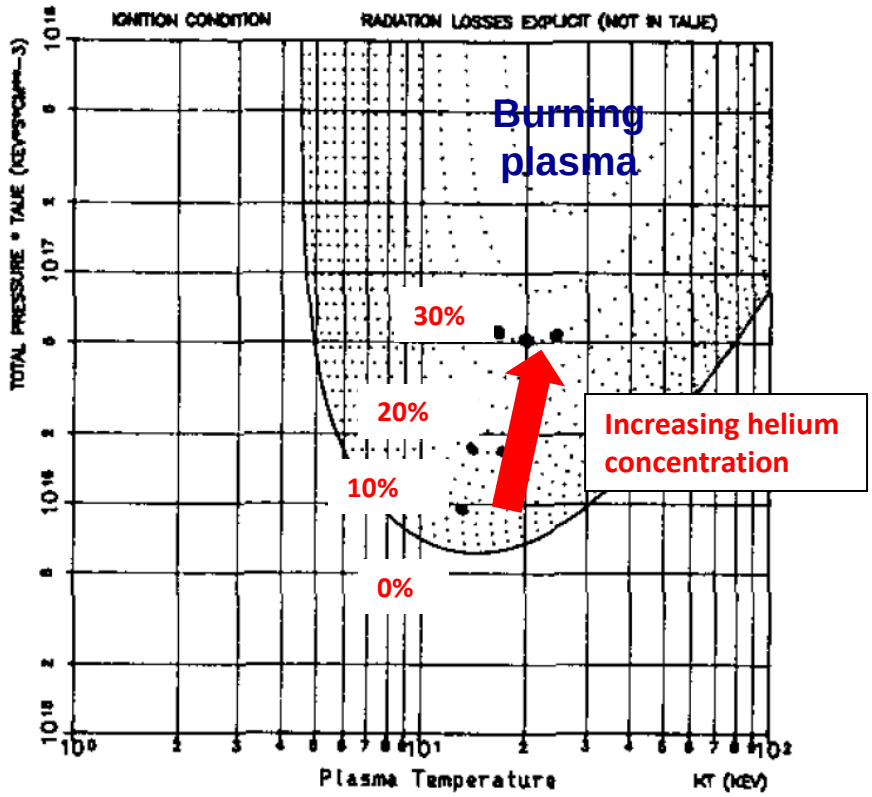
Motivation: Helium ash has to be exhausted efficiently in future burning plasma experiments and fusion reactors



Pressure x energy confinement time

Plasma temperature

[Reiter, D. et al., PPCF 33 (1991) 13, 1579]

Effective helium confinement time is a key quantity to qualify island divertor

$$\tau^*_{He} = \tau_\alpha + R/(1-R)\tau_{He}$$

Core α-source and confinement

Recycling, re-fueling and **exhaust** from SOL

Addressed in experiments

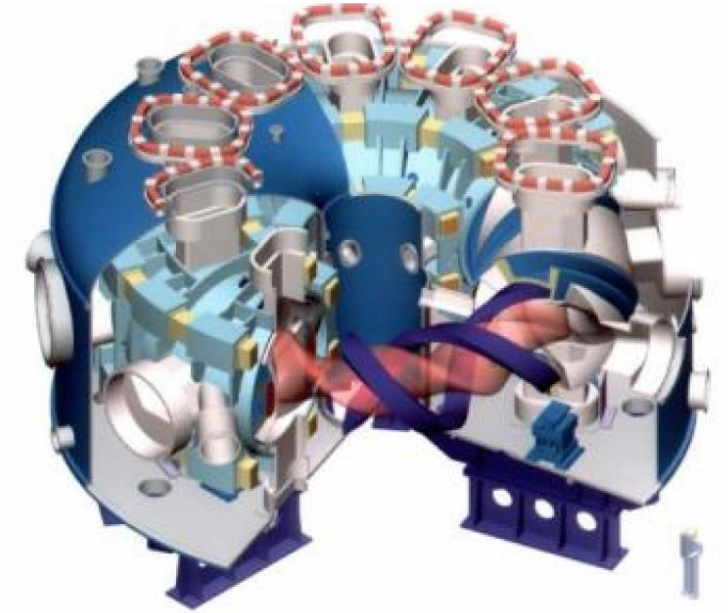
Consider: typical helium exhaust efficiency <10% results in priority on edge exhaust and re-fueling aspects

Experiments at TEXTOR and LHD aim on testing the impact of RMP fields on helium transport and exhaust in the plasma edge

TEXTOR and LHD enable studying helium exhaust with RMP fields in two complementary plasma boundary solutions

Large Helical Device (LHD)

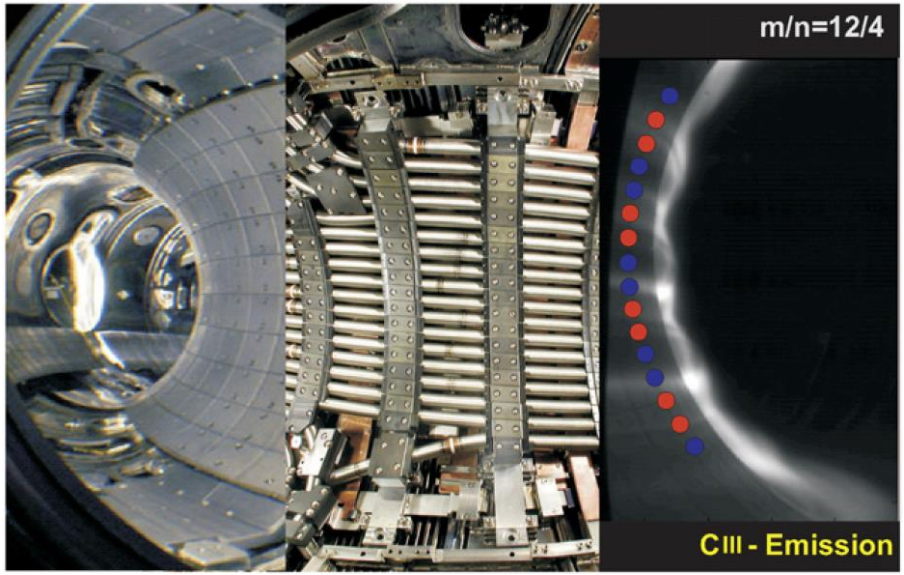
Heliotron device (2/10 twist) with closed helical divertor



- Closed Helical Divertor
- Stochastic edge with magnetic islands

TEXTOR-DED

Circular tokamak plasma with stochastic boundary and pumped limiters



- ALT-II pumped limiter
- Dynamic Ergodic Divertor (DED) with m/n=12/4, 6/2 or 3/1 base mode

RMP fields are considered for ITER as ELM control tool and impact on helium exhaust in D-T phase needs to be addressed

Outline of talk

- **TEXTOR and LHD as comparative test cases for investigation of helium exhaust and helium transport features**
- **Helium exhaust with an edge magnetic island at TEXTOR**
- **Helium exhaust with edge magnetic island and magnetic field stochasticity at LHD**
- **Conclusions**

- **Method: puff/pump study** (~10^{19} atoms/s for 100-150 ms)
- **Metrics:**
  - **Plasma density**
  - **Neutral pressure**
  - **He-I & He-II emission**
  - **Helium density**
  - **He/(He+H) ratio**

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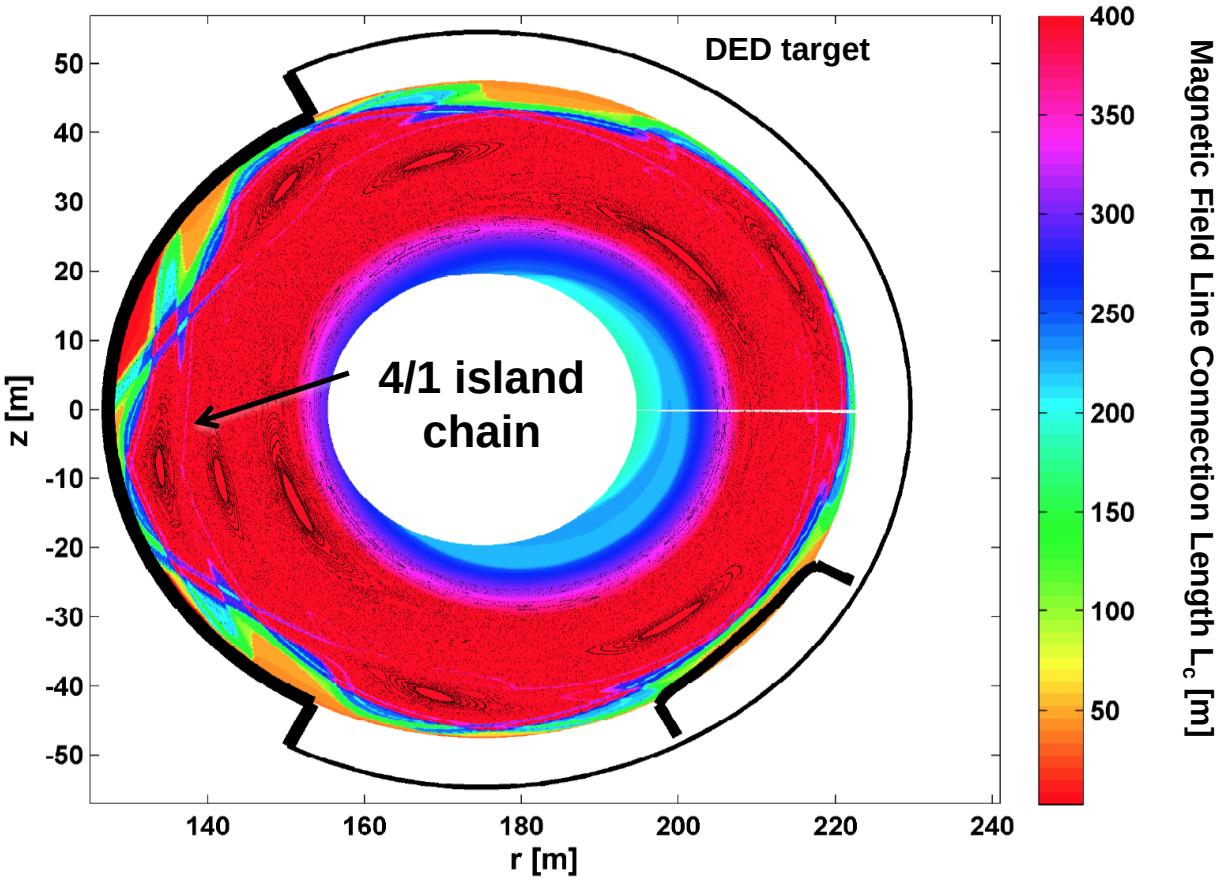
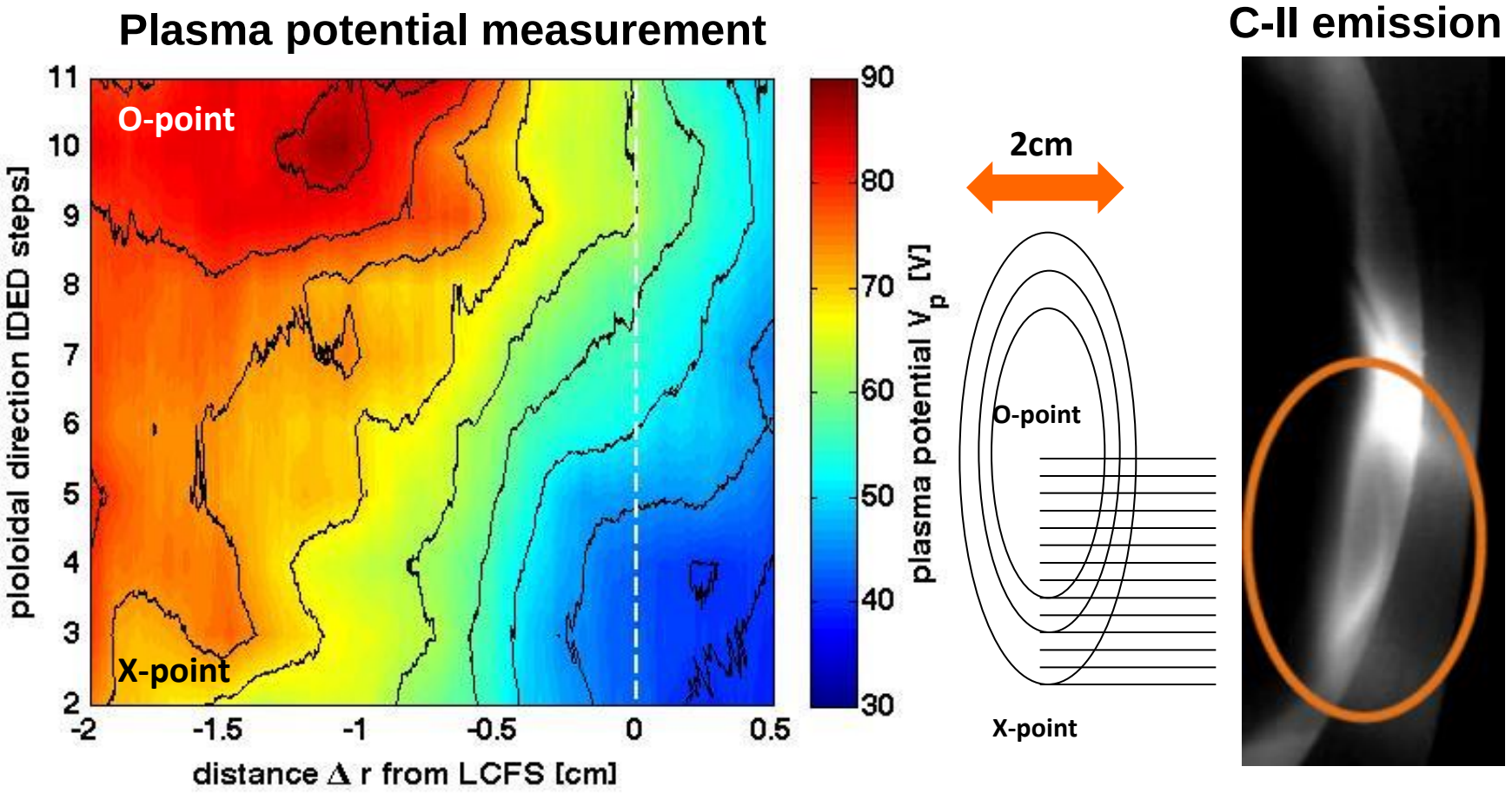
An edge magnetic islands was generated reliably at TEXTOR

[Schmitz, O.. et al., NF 56 (2016) 106011]

Magnetic field line connection length



Magnetic island yields significant poloidal potential variation

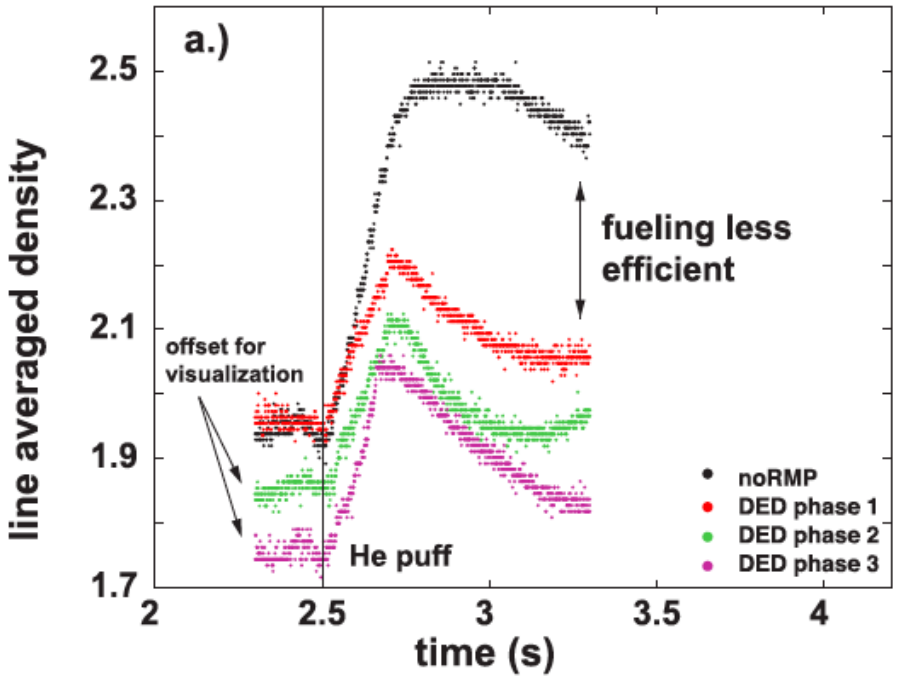


- Electric fields from island center to X-point of ~ +2-20 V/cm
- ORBIT finds dominant electron loss for T_e/T_i ratio [Ciacio, G. et al., PoP 22 (2015) 102516]
- τ_π drops by 30% with island - refueling of plasma is hardly possible [Schmitz, O.. et al., NF 56 (2016) 106011]

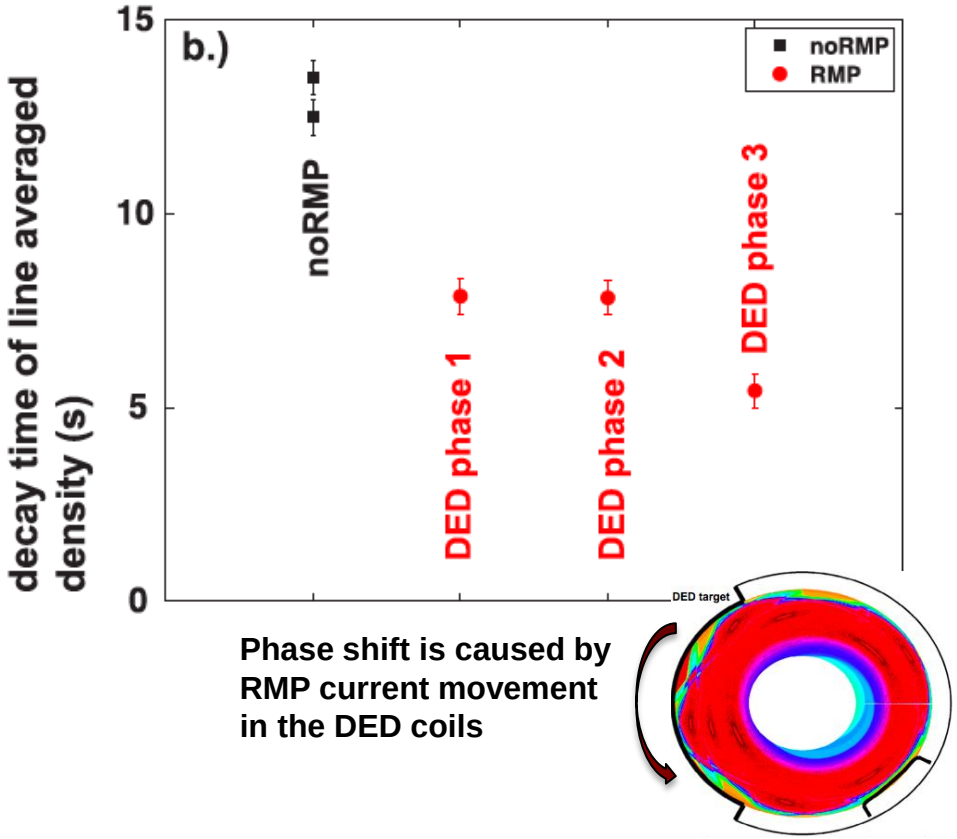
Helium puff/pump study at TEXTOR-DED shows substantial reduction of helium confinement with island present

[Schmitz, O.. et al., NF 56 (2016) 106011]

Line averaged density



Density decay rate



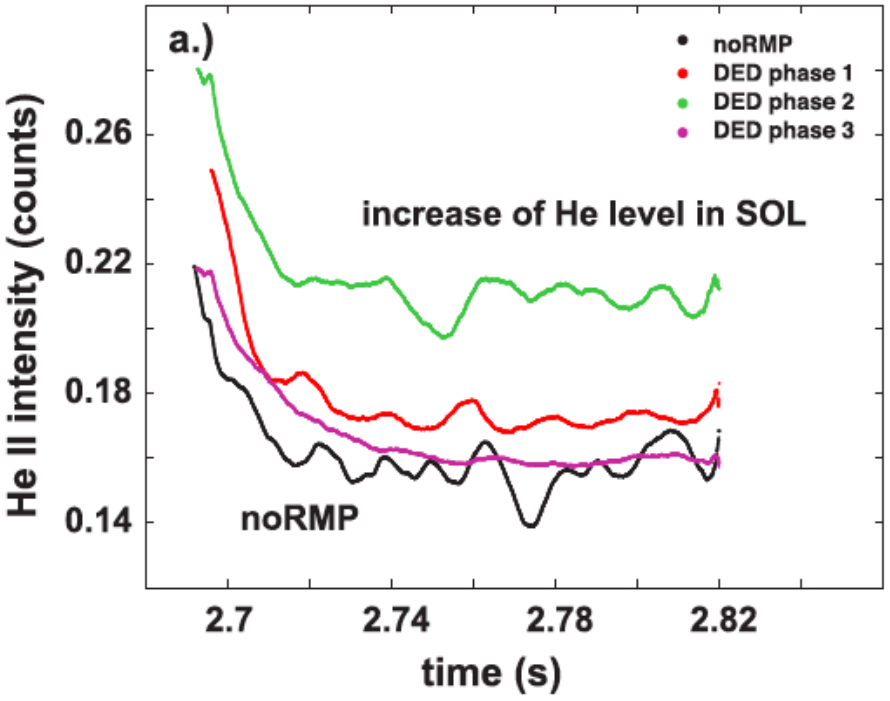
Phase shift is caused by RMP current movement in the DED coils

Island enhances outward transport and yields reduced fueling efficiency

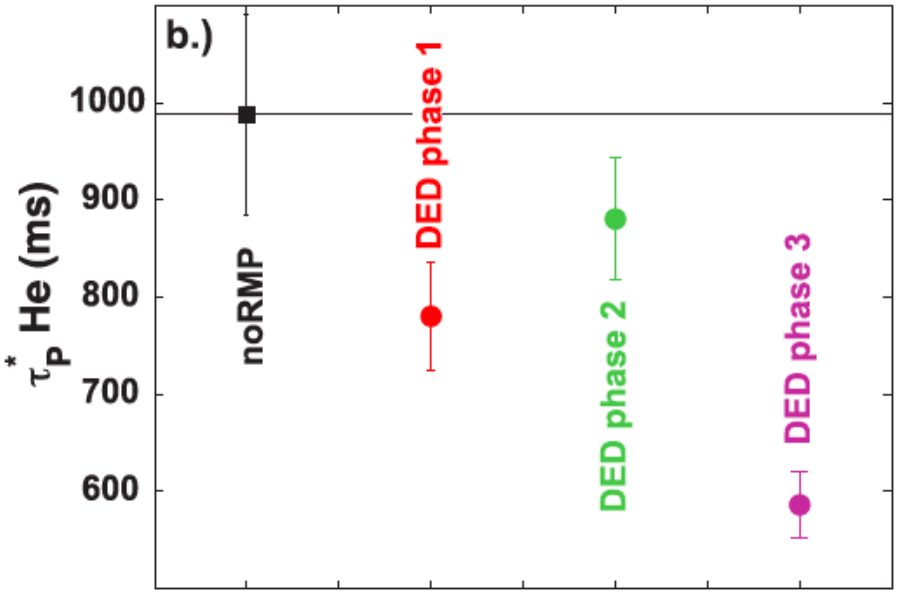
Helium is flushed outward into the plasma edge with overall reduced helium confinement times

[Schmitz, O.. et al., NF 56 (2016) 106011]

He-II (468nm) intensity in edge



τ_p* for He in edge

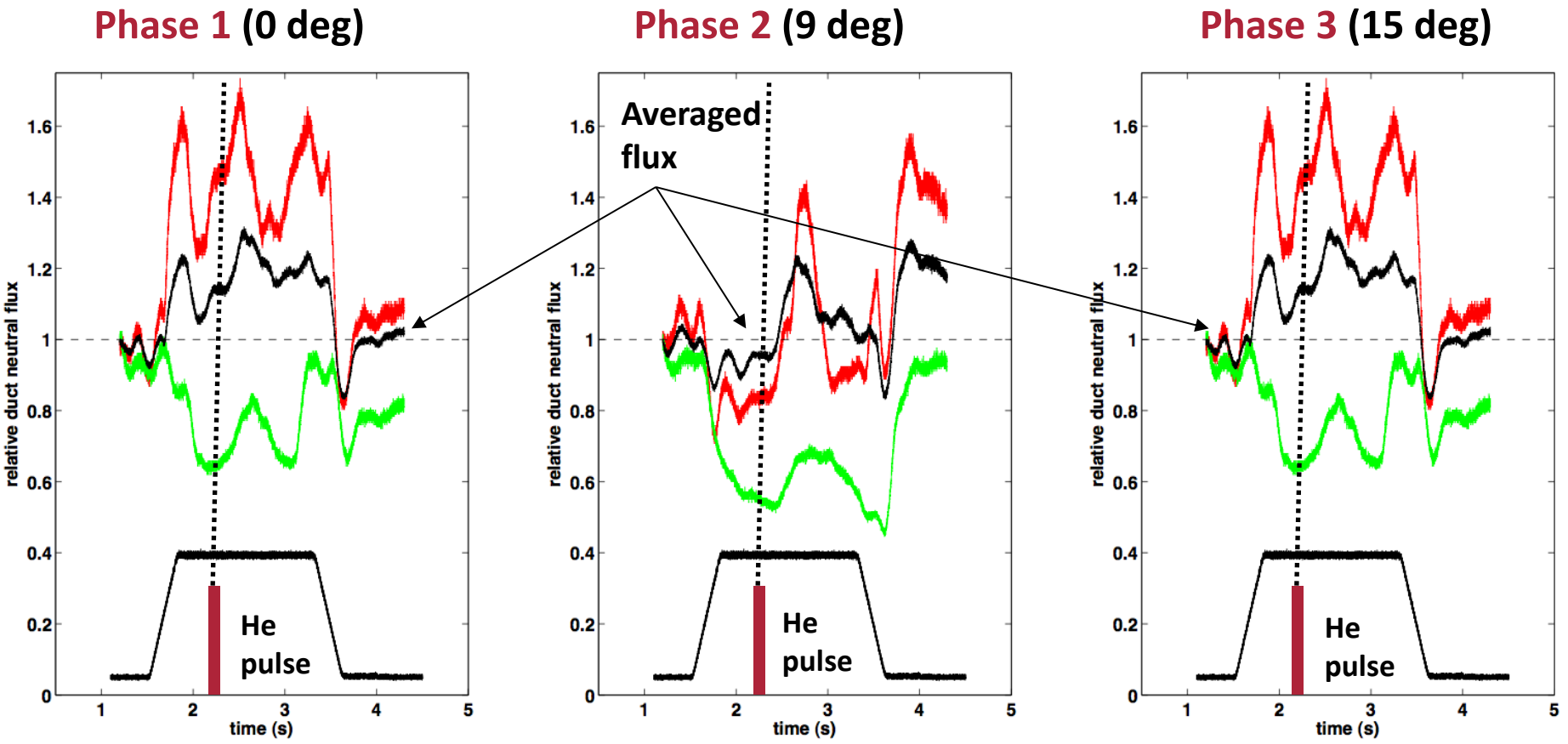


Helium exhaust from plasma and retention in plasma periphery is enhanced with a magnetic edge island at TEXTOR

There is a sensitivity to the RMP phase

Edge magnetic island couples to toroidally located pumping capacity in a dedicated way demonstrating 3-D effect on helium exhaust

Relative neutral flux in adjacent ALT-II ducts for blade 5 (247.5deg) and blade 6 (225 deg)



Averaged flux across all Penning gauges shows 25% increase of He pulse exhaust for optimal phasing

[Schmitz, O.. et al., NF 56 (2016) 106011]

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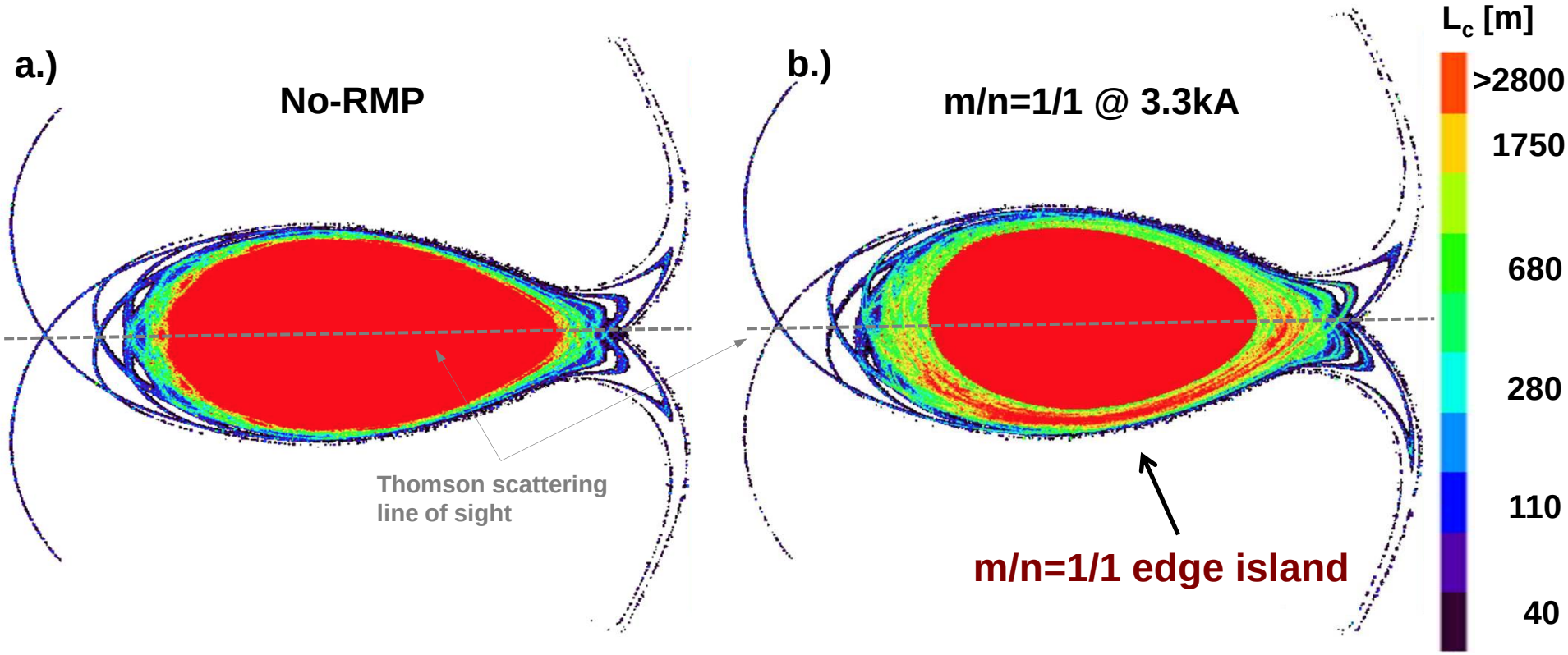
In LHD experiment, the penetrated edge magnetic island has a clear signature in magnetic connection length plot

Magnetic field line connection length show m/n=1/1 island structure



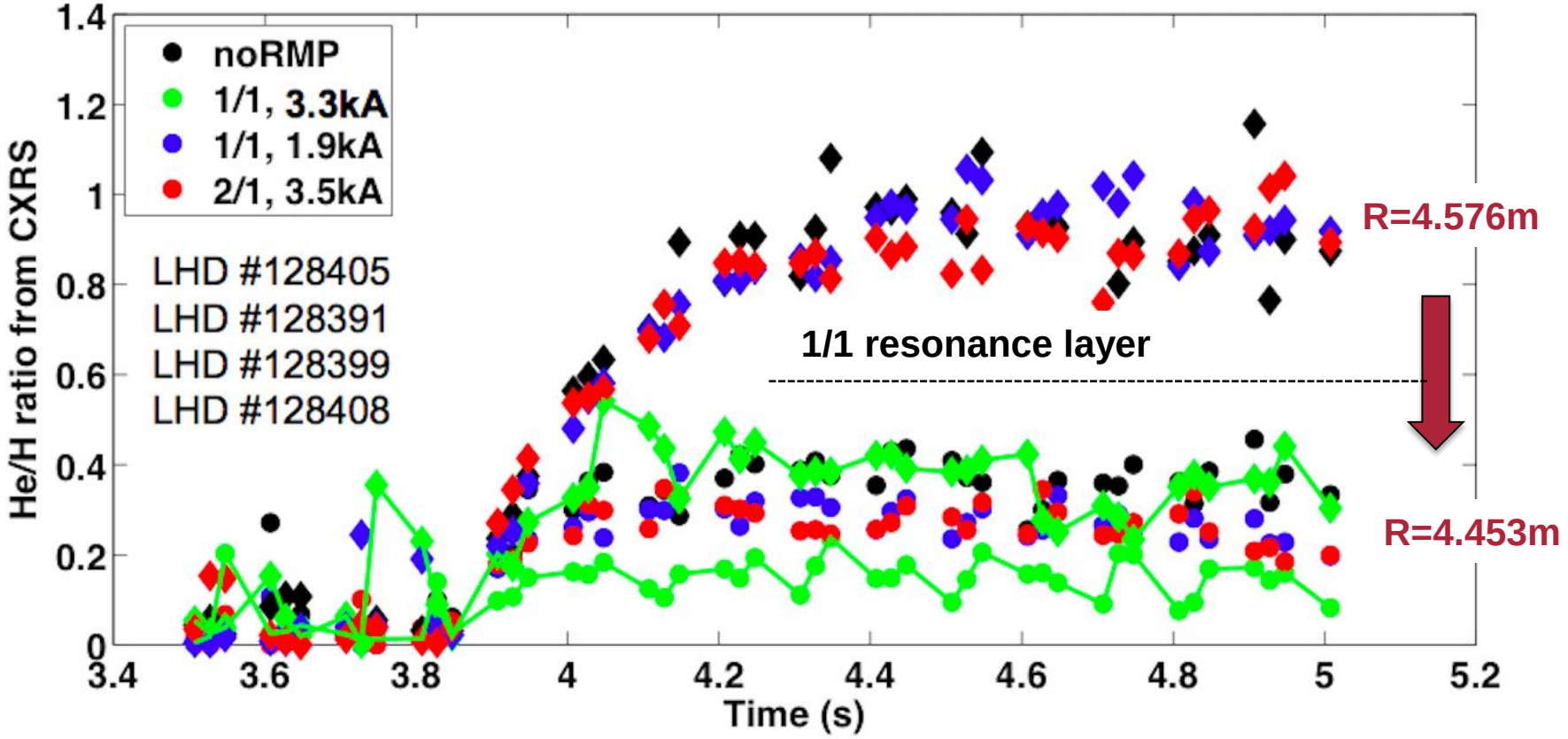
Three magnetic topologies were addressed:

(1) Penetrated edge island at 1/1 resonance
(2) Healed edge island on 1/1 resonance
(3) Healed core magnetic island on 2/1 resonance

[Schmitz, O.. et al., NF 56 (2016) 106011]

Penetrated magnetic island acts as barrier for helium back penetration into the plasma core

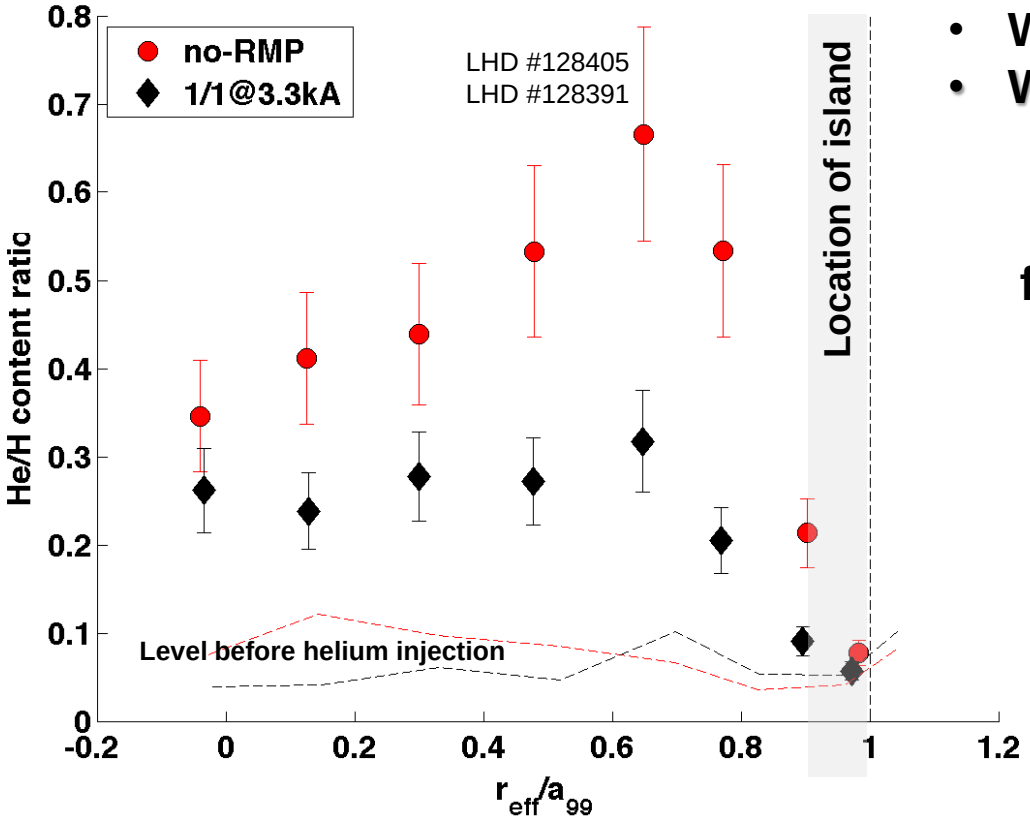
[Schmitz, O.. et al., NF 56 (2016) 106011]



Retention of He in the plasma periphery is enhanced which allows for better pumping

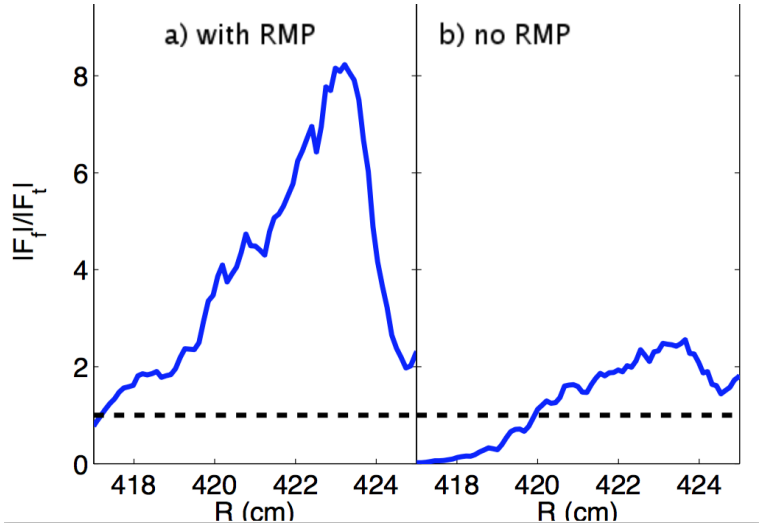
Strong reduction of helium content is measured along the entire radius by the LHD-CXRS system

[Schmitz, O.. et al., NF 56 (2016) 106011]



- Without RMP: **He accumulating**
- With RMP: **strong decontamination**

EMC3-EIRENE: increased ratio of friction vs. thermal force with RMP



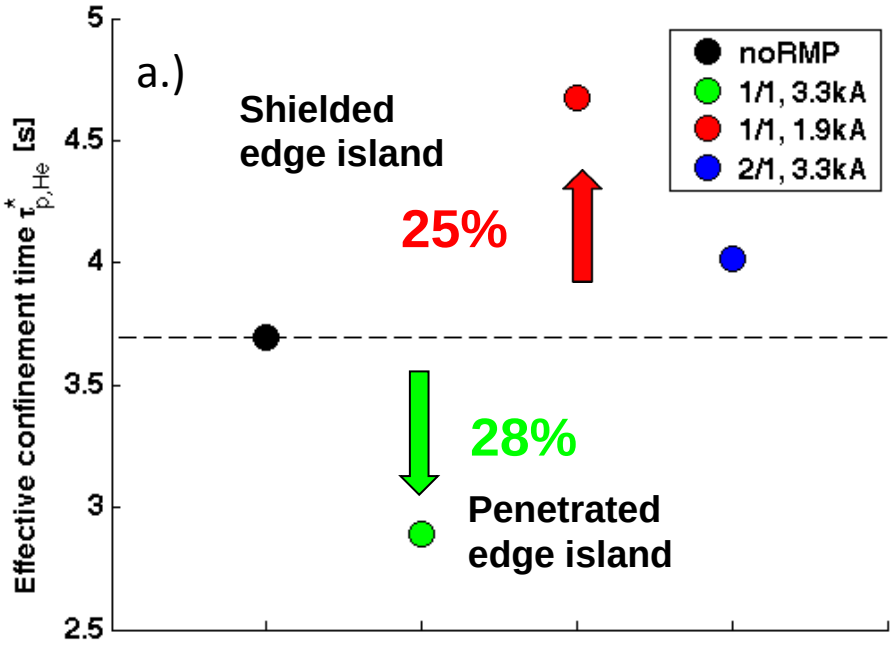
[Bader, A.. et al., PPCF 58 (2016) at press]

Evidence for enhancement of outward transport of helium by the edge magnetic island

Penetrated edge magnetic island shows 20% reduced effective helium confinement time $\tau_{p,He}^*$

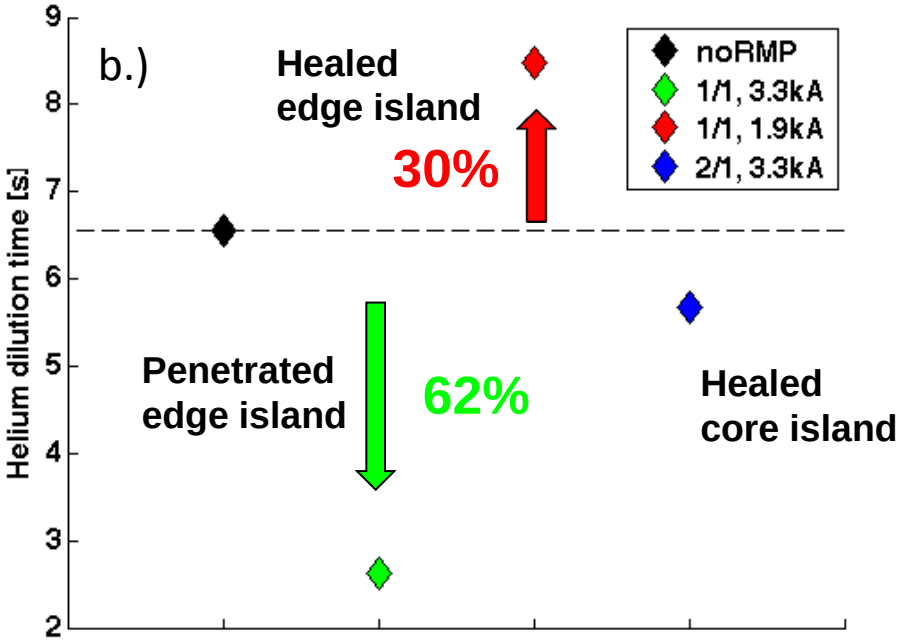
Effective helium confinement time

From e-fit to He-I intensity



Helium dilution time

From e-fit to He/(He+H) ratio from CXRS



Results are in line with radiation trapping in RMP assisted detachment

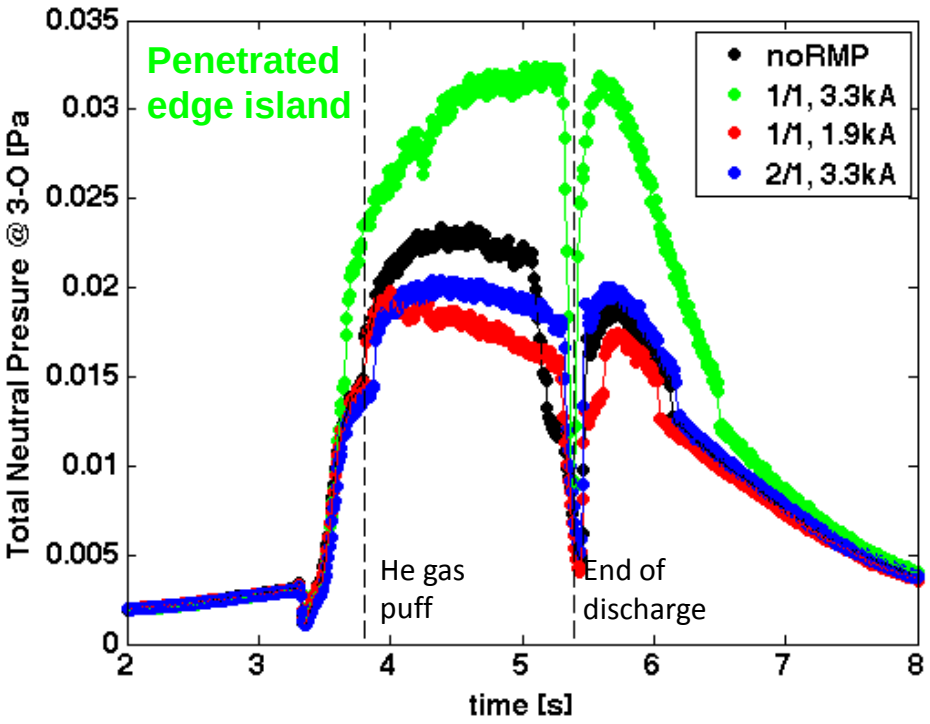
[Kobayashi, M. et al., Nuclear Fusion 53 (2013) 093032]

Increased time scales for healed island cases is an open question

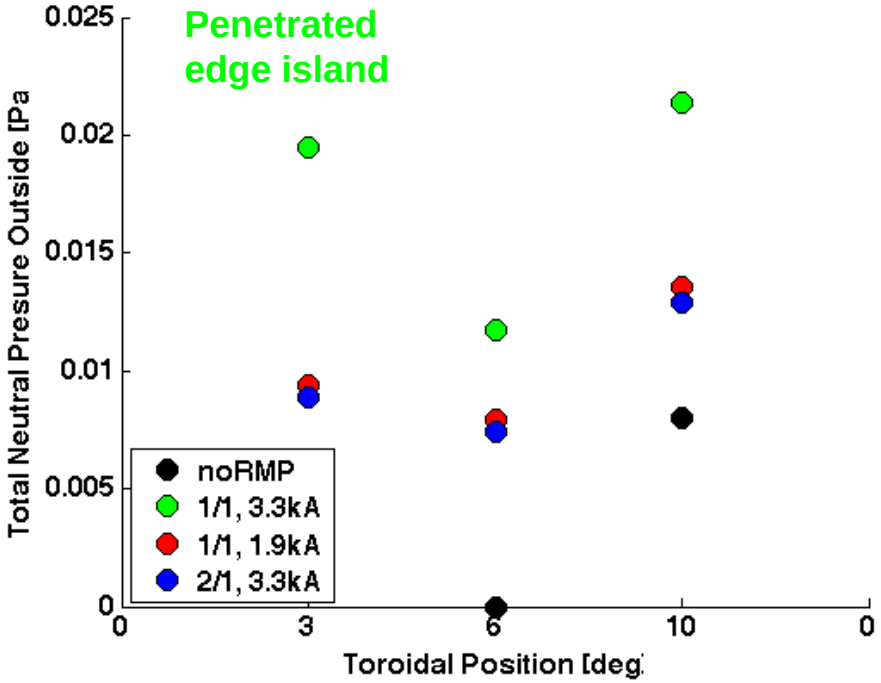
Penetrated edge magnetic island yields strong increase of total neutral pressure along entire torus

[Schmitz, O.. et al., NF 56 (2016) 106011]

Total neutral pressure in main chamber



Averaged total neutral pressure in main chamber along torus

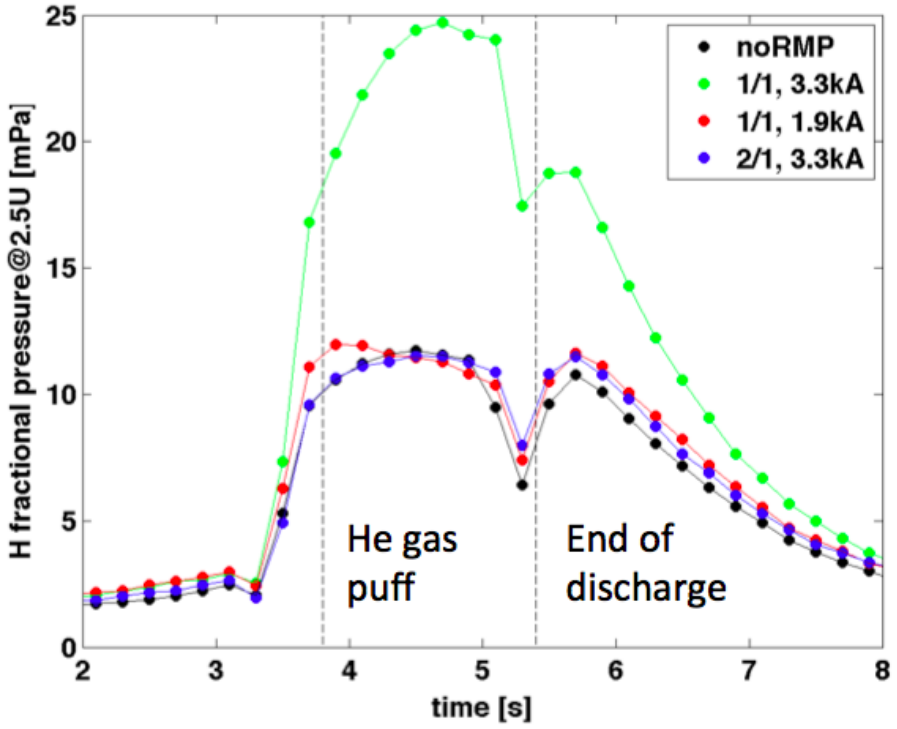


Penetrated edge island significantly enhances He retention in plasma periphery (puff rate was constant)

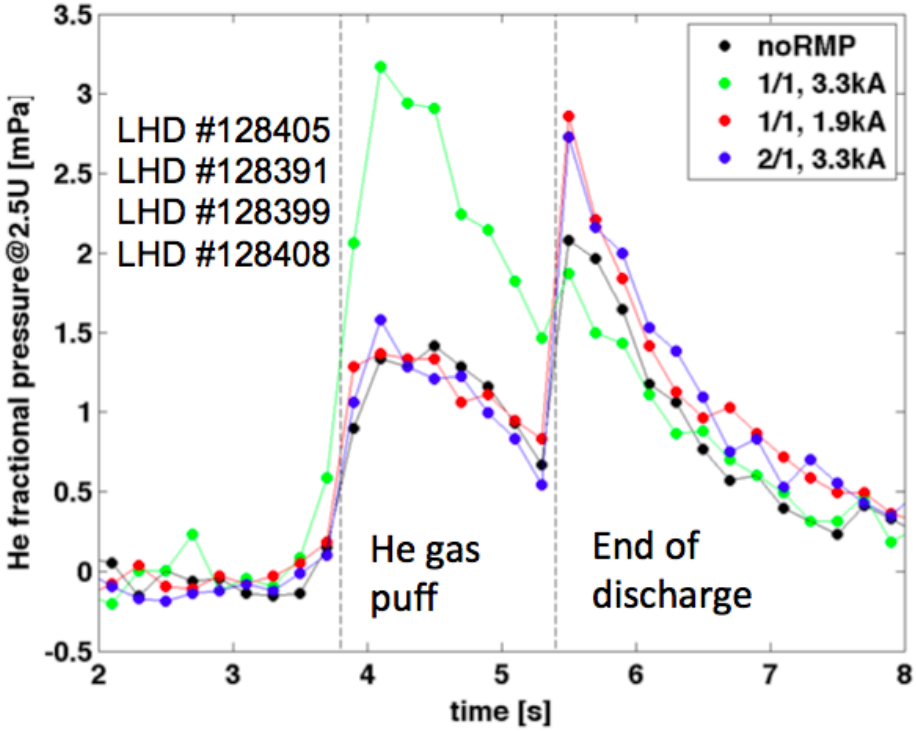
Evidence for accumulation of helium in far-SOL is provided from spectroscopically assisted Penning gauges

[Schmitz, O.. et al., NF 56 (2016) 106011]

Hydrogen fractional pressure in main chamber



Helium fractional pressure in main chamber

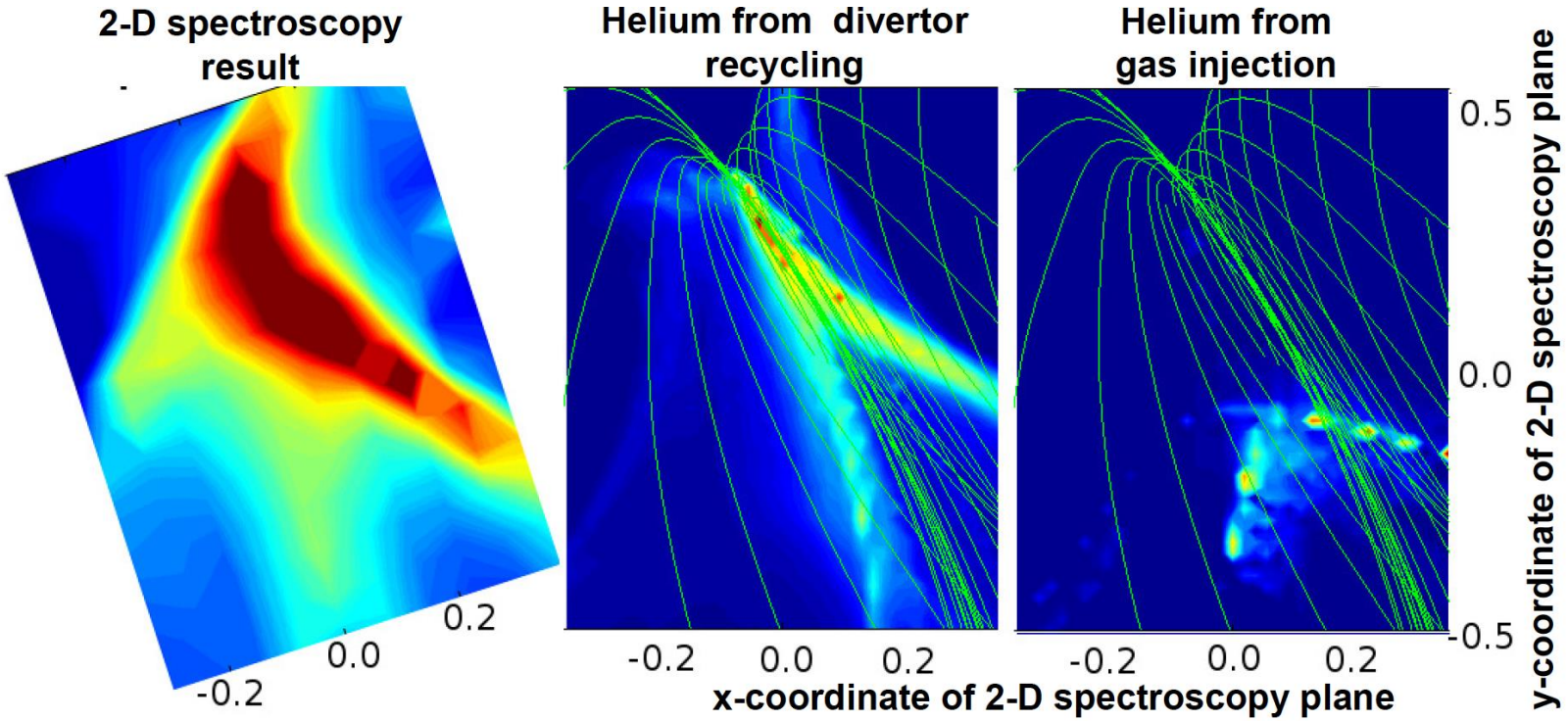


Fractional neutral pressures of hydrogen and helium are increased in the plasma periphery.

Also measured in divertor chamber!

EMC3-EIRENE modeling supports dominant role of He recycling

Helium recycling is the main fueling term for the edge helium population based on synthetic reconstruction of He-I emission (667.8nm)

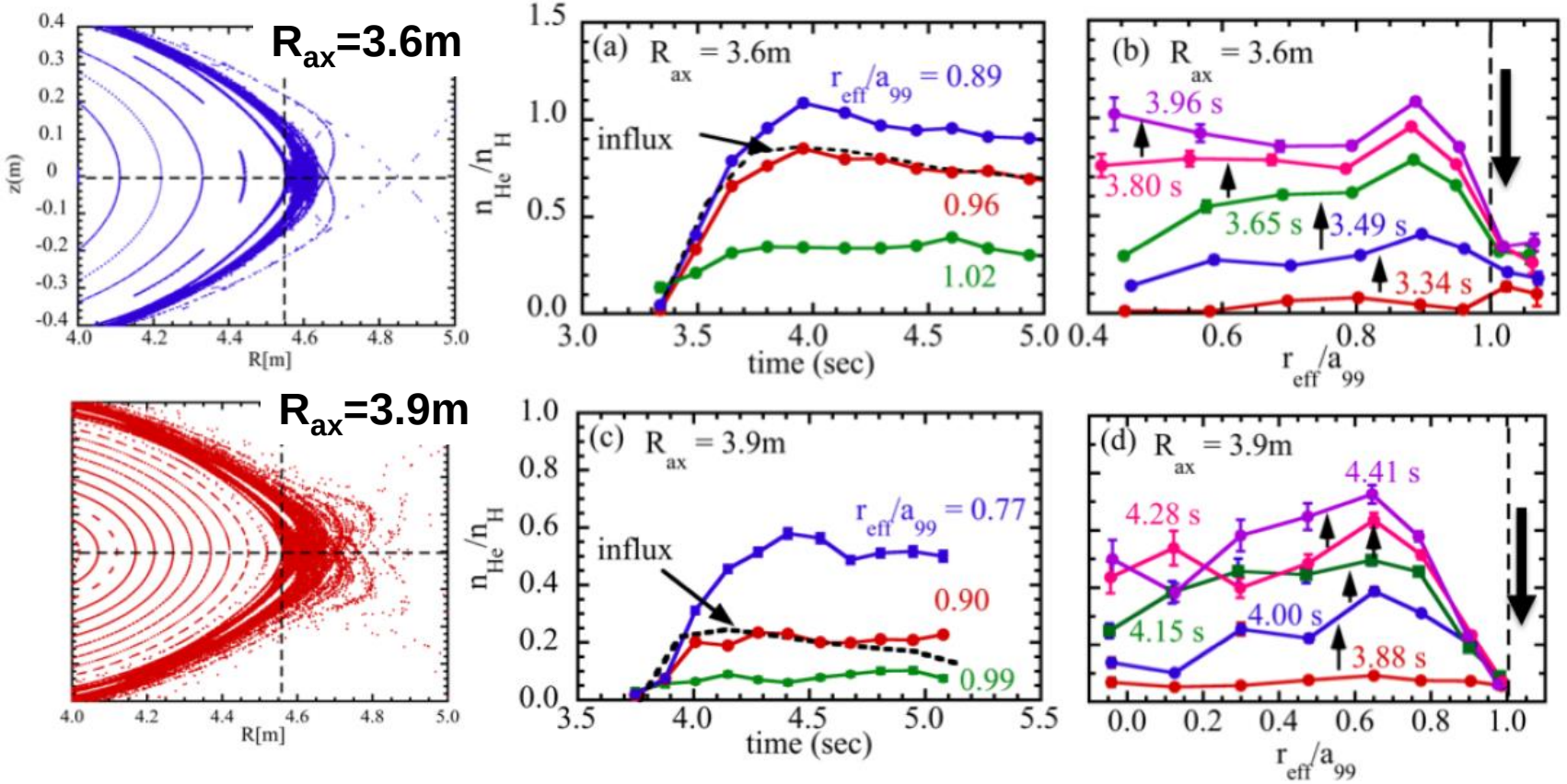


[Bader, A.. et al., PPCF 58 (2016) at press]

- EMC3-EIRENE result supports dominant role of He recycling on He fueling
- Core fueling source needed mimicking He core level from ion-root transport

Increased width of stochastic layer also aids reduced helium density in plasma core without magnetic island

Stochastic layer width at LHD is controlled by position of the magnetic axis



Intrinsic stochastic layer at LHD can be tuned to yield significant helium decontamination as well

[Ida, K.. et al., PPCF 58 (2016) 074010]

Conclusions

- Experiments at TEXTOR and LHD show strong impact of edge magnetic islands and field stochasticity on helium fueling and exhaust
- TEXTOR results provide evidence for importance of link between 3-D plasma edge structure and pumping device
- LHD results highlight the role of islands for retaining helium in the scrape-off layer and reducing helium back-fueling efficiency (including EMC3-EIRENE)
- EMC3-EIRENE supports for LHD dominant role of fueling from recycled helium and suggests increased friction force enhancing outward helium transport

➡ Findings from both experiments and EMC3-EIRENE modeling support:

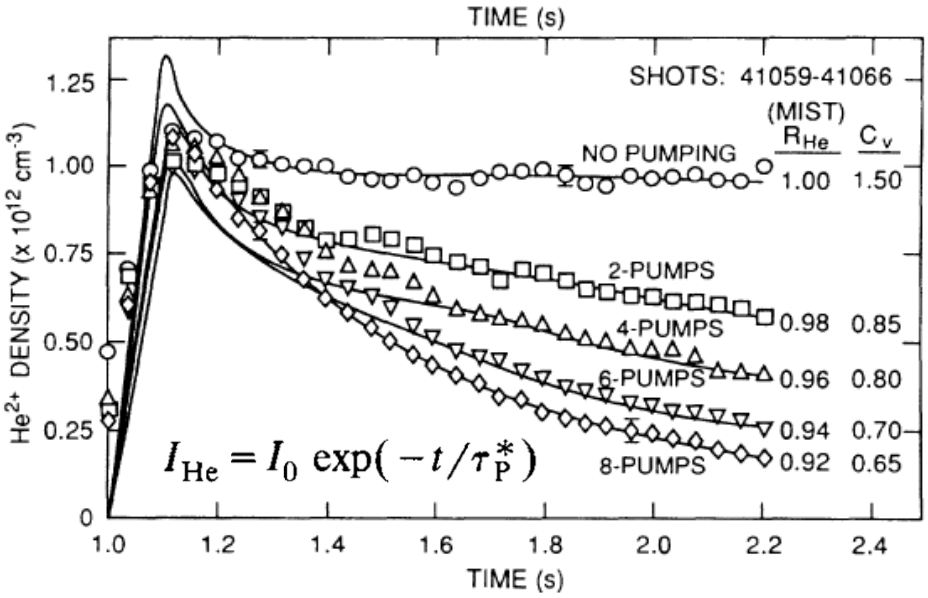
Selectively enhanced outward He transport	Reduced He fueling	Increased overall collection efficiency

➡ This study suggests RMP fields as flexible actuator to improve He exhaust during RMP ELM control at ITER and beyond

Appendix

Motivation II: Experimental quantification of helium exhaust

Gas puff experiments were used to demonstrate and quantify helium exhaust



[Hillis, D. et al., PRL 65 (1990) 16, 2382] **TEXTOR**

[Bosch, H.-S. et al., PPCF 39 (1997) 1771-1792] **Asdex-Upgrade**

[Wade, M. et al., PRL 74 (1999) 2702-2705] **DIII-D**

Exhaust efficiency is function of neutral pressure, pumping efficiency and flux

$$\epsilon_{He} = p_{(0,He)} \cdot S_{eff}/\Gamma_{He}$$

In-situ calibration

Neutral pressure gauges with fractional pressure capacity

Spectroscopy

Exhaust efficiency is a combination of scrape off layer (SOL) and pump exhaust

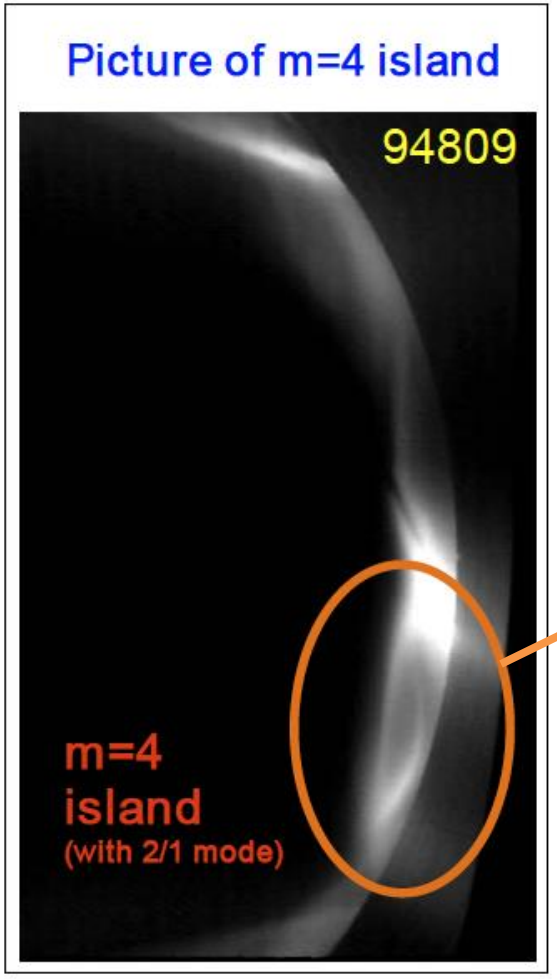
$$\epsilon_{He} = \epsilon_{SOL} \cdot \epsilon_{Pump}$$

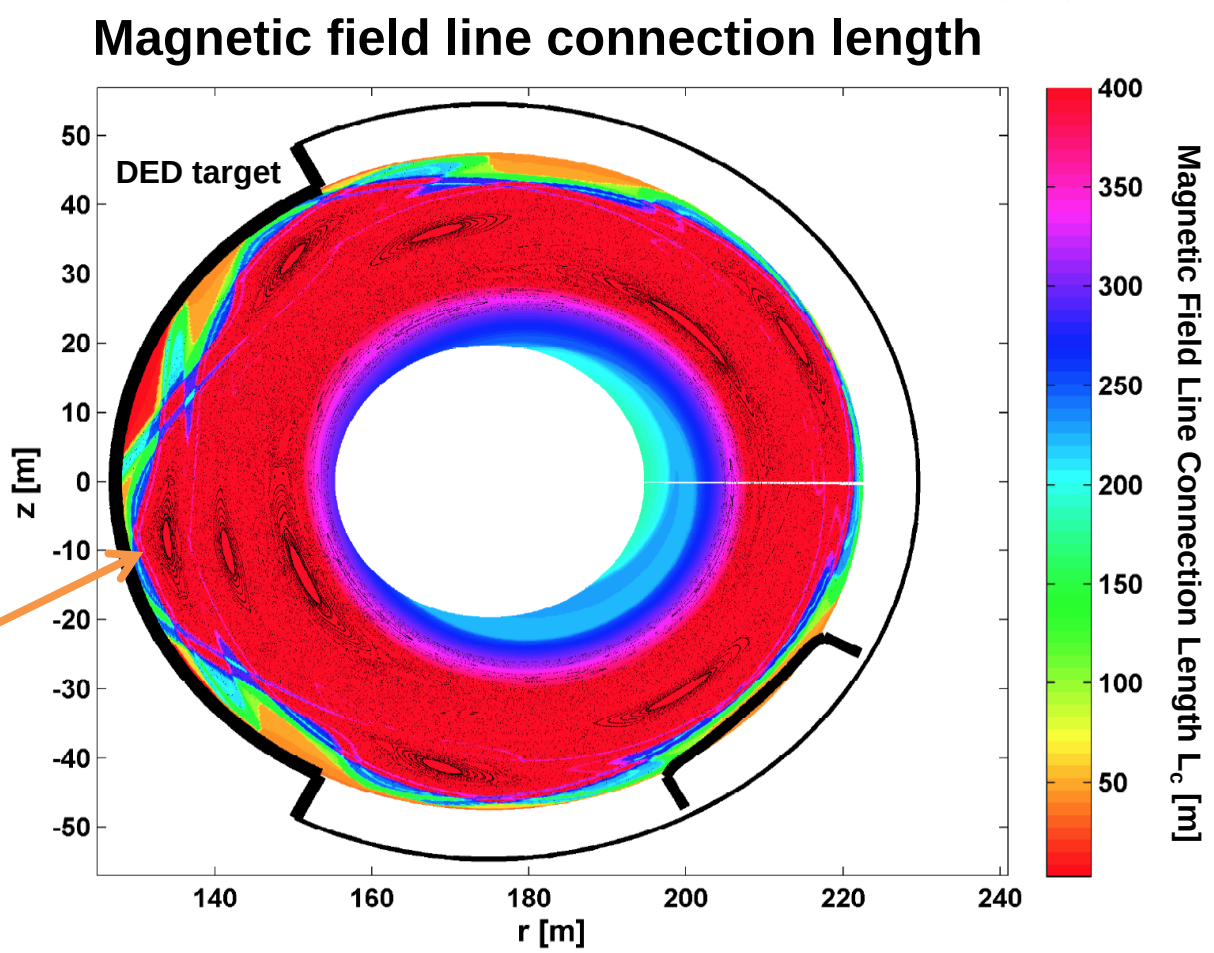
[Samm, U. et al., JNM 196-198 (1992) 633]

Method: puff/pump studies to measure exhaust time scales and characterize the dynamics of the neutral particle reservoir

An edge magnetic islands was generated reliably at TEXTOR

[Schmitz, O.. et al., NF 56 (2016) 106011]



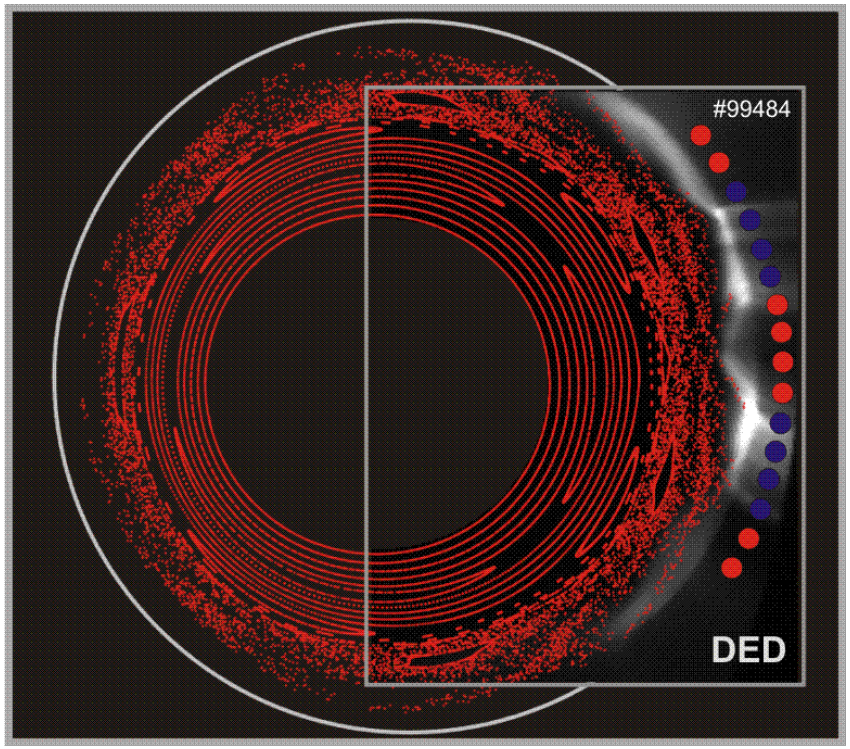


Magnetic island was identified in C-III light emission as well as in plasma profile and plasma potential measurements

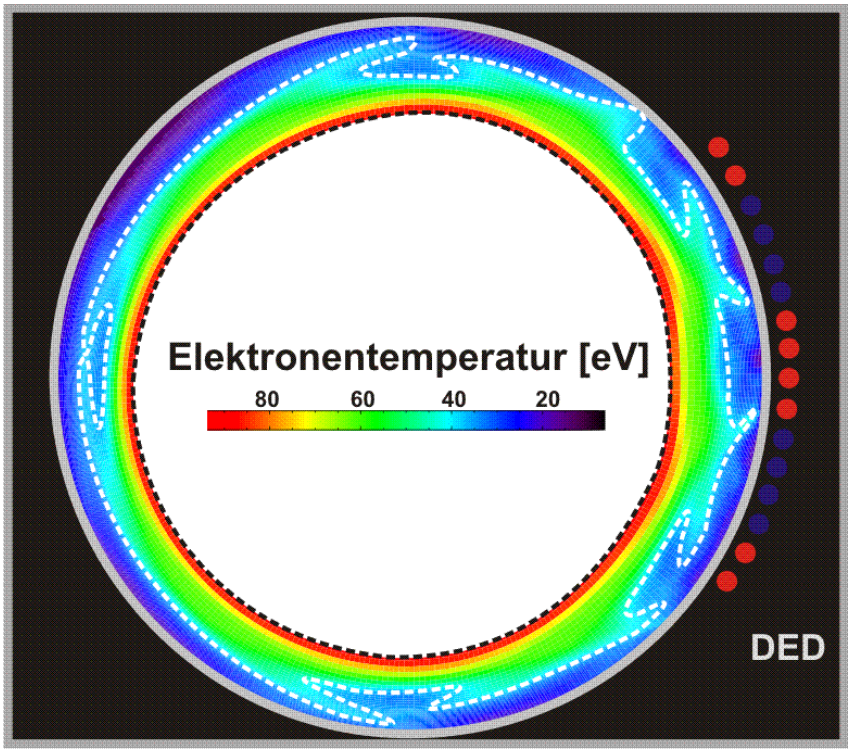
TEXTOR-DED features a stochastic boundary

Perturbed plasma edge layer features magnetic islands (plasma core and plasma boundary), stochasticity and helical SOL

Poincare plot of magnetic topology



Electron temperature from EMC3-EIRENE

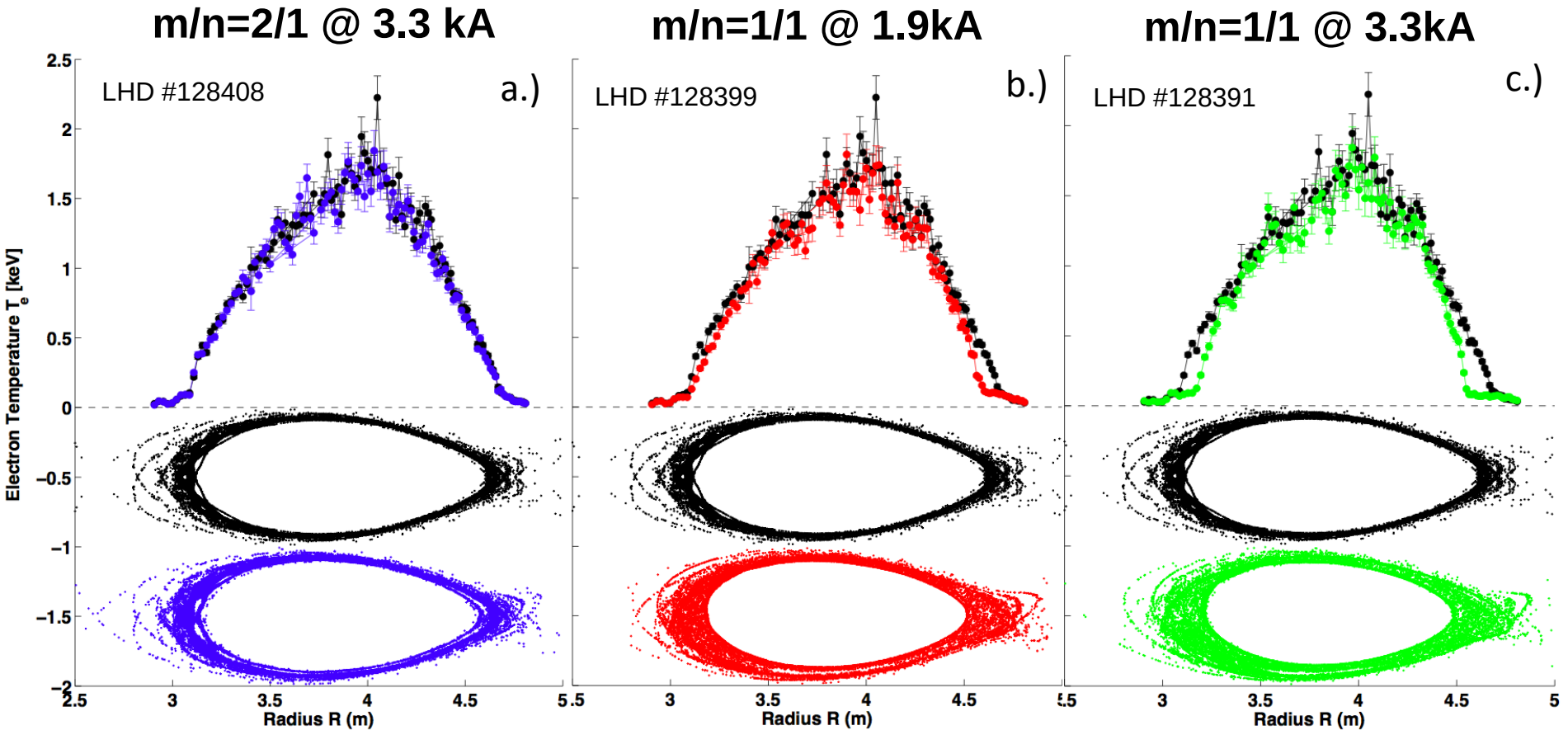


[Schmitz, O.. et al., NF 48 (2008) 024009]

The short connection length domain (helical SOL) governs the edge transport characteristics at TEXTOR-DED in most cases

In LHD experiment, the penetrated edge magnetic island shows clear flattening of electron temperature profile

[Schmitz, O.. et al., NF 56 (2016) 106011]



Both RMP configurations show evidence for plasma screening/island healing from magnetics

Edge island penetrated

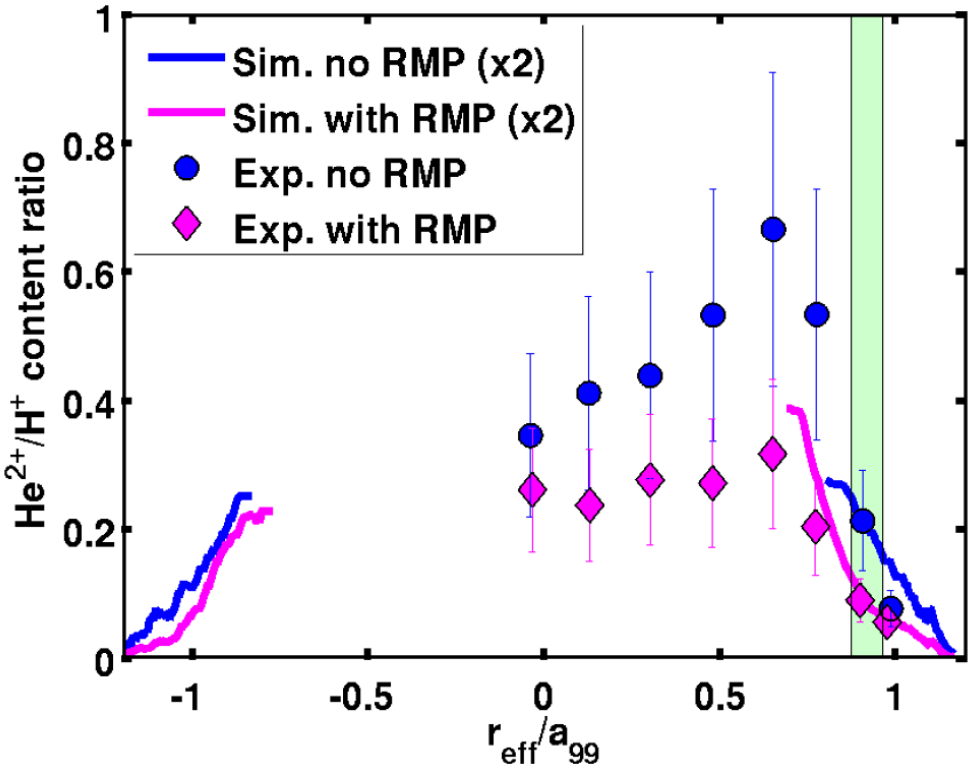
Magnetics support this assessment of island penetration

A-

Core helium fueling important in EMC3-EIRENE modeling

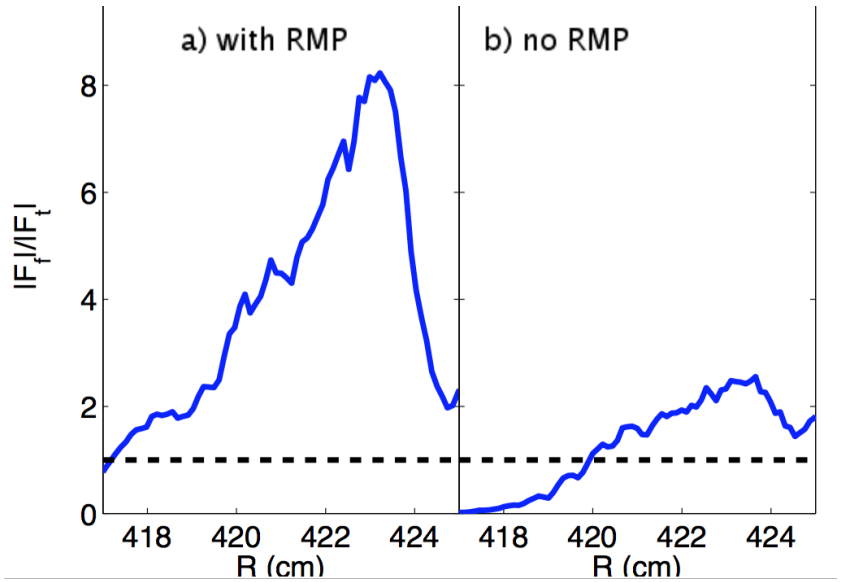
Adding a core He source is needed for a reasonable match between modeled and measured He/H profiles in the plasma edge

[Bader, A.. et al., PPCF 58 (2016) at press]



Represents experimental core helium level from ion root impurity transport in EMC3-EIRENE (edge model)

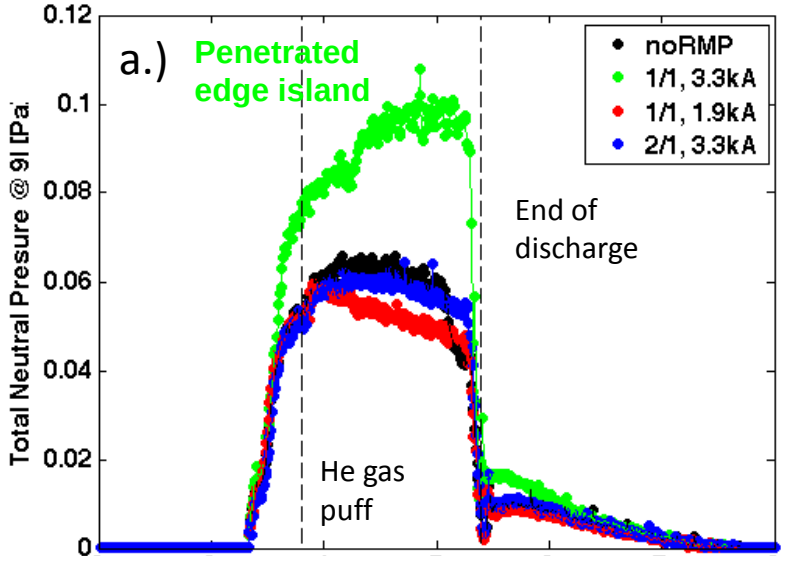
Drive term: increased friction force with RMP field

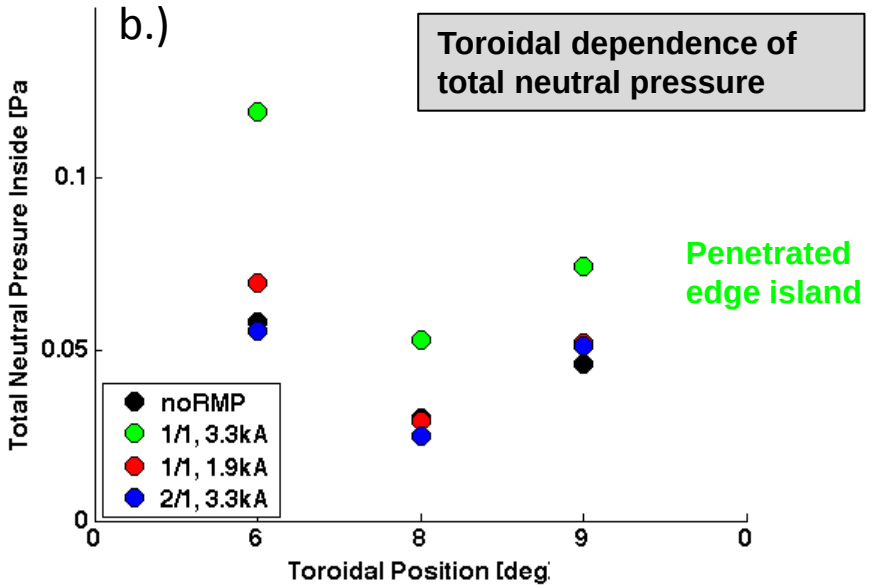


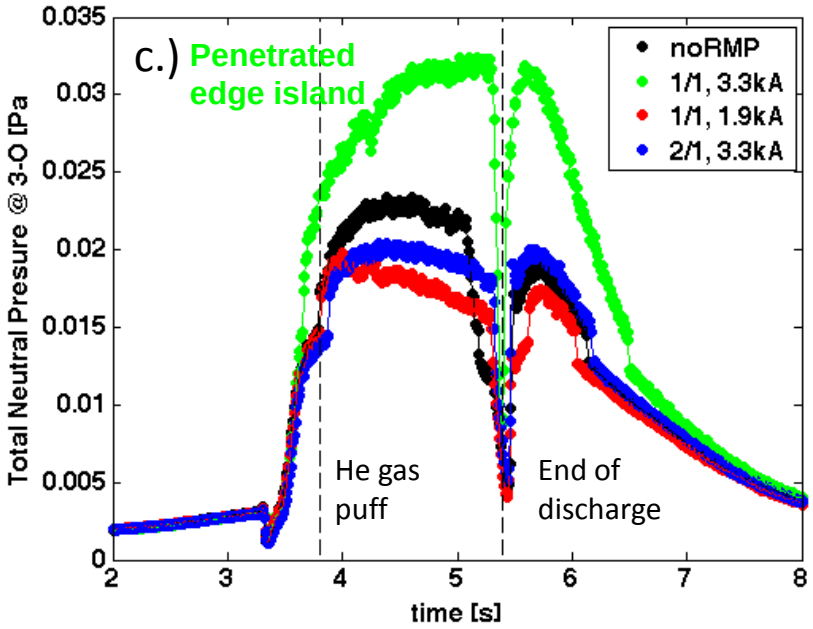
Detailed studies on helium transport ongoing

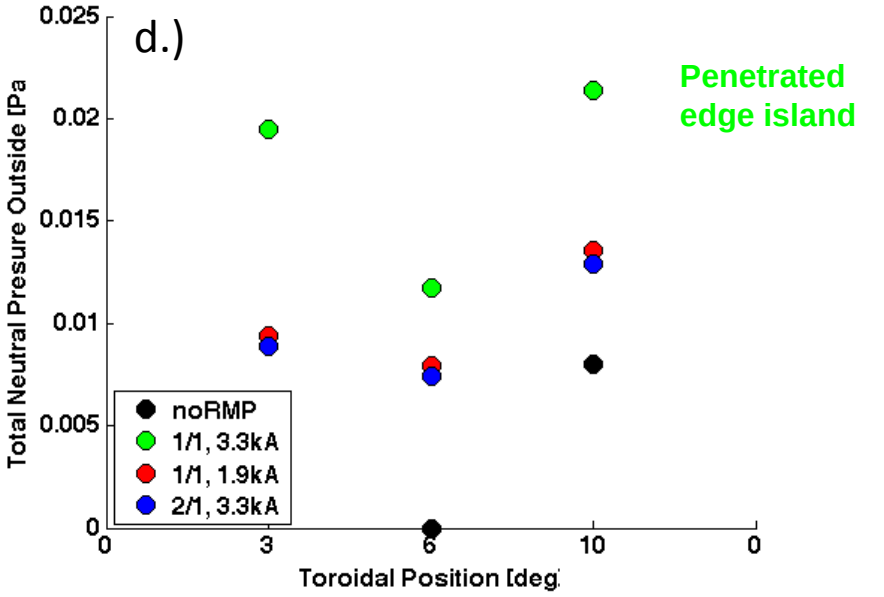
Penetrated edge magnetic island (m/n=1/1) shows strongly increased total neutral pressure along torus

[Schmitz, O.. et al., NF 56 (2016) 106011]





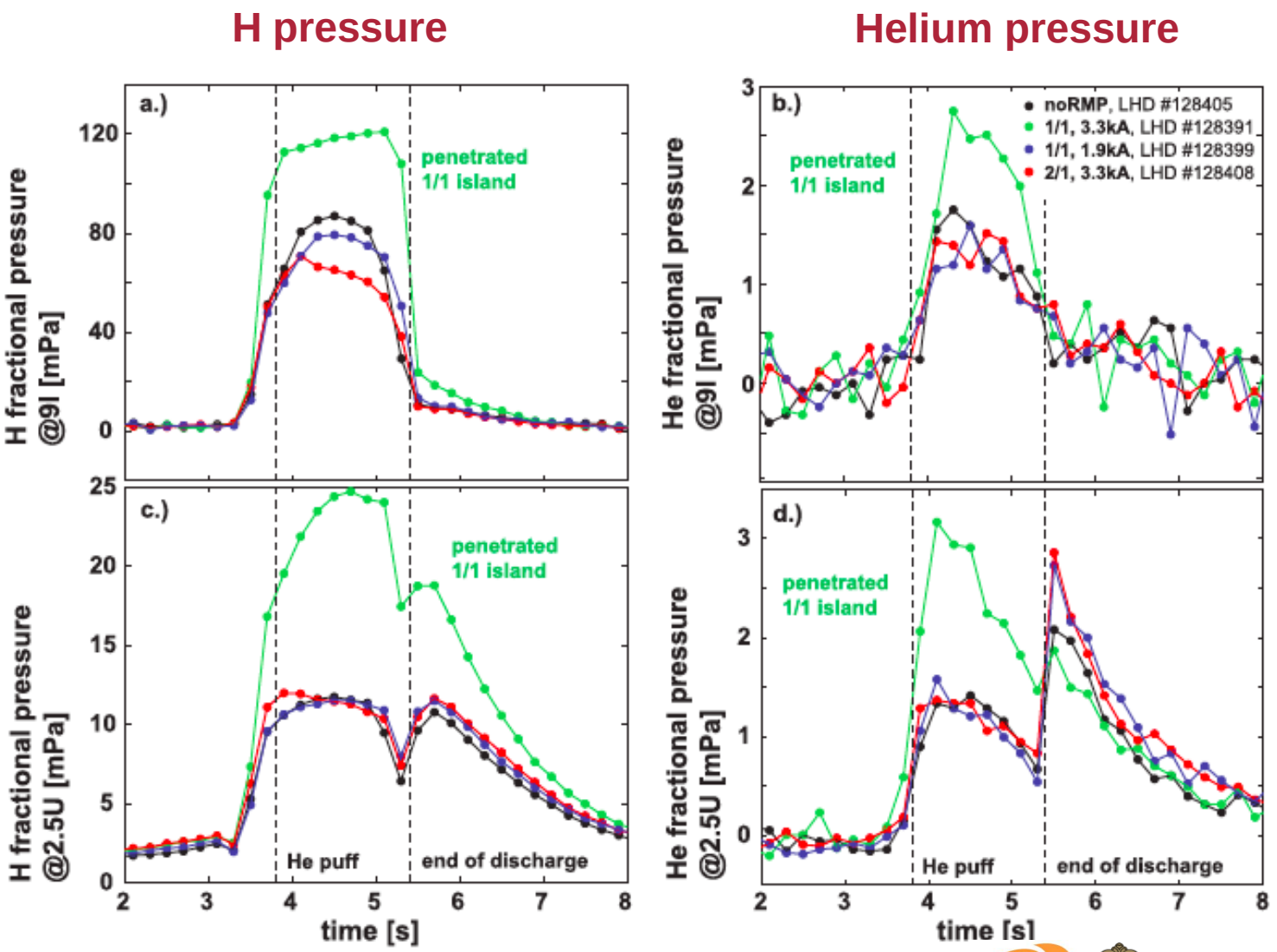




Evidence for accumulation of helium in far-SOL is provided from spectroscopically assisted Penning gauges

Inside of divertor chamber

Inside of main chamber

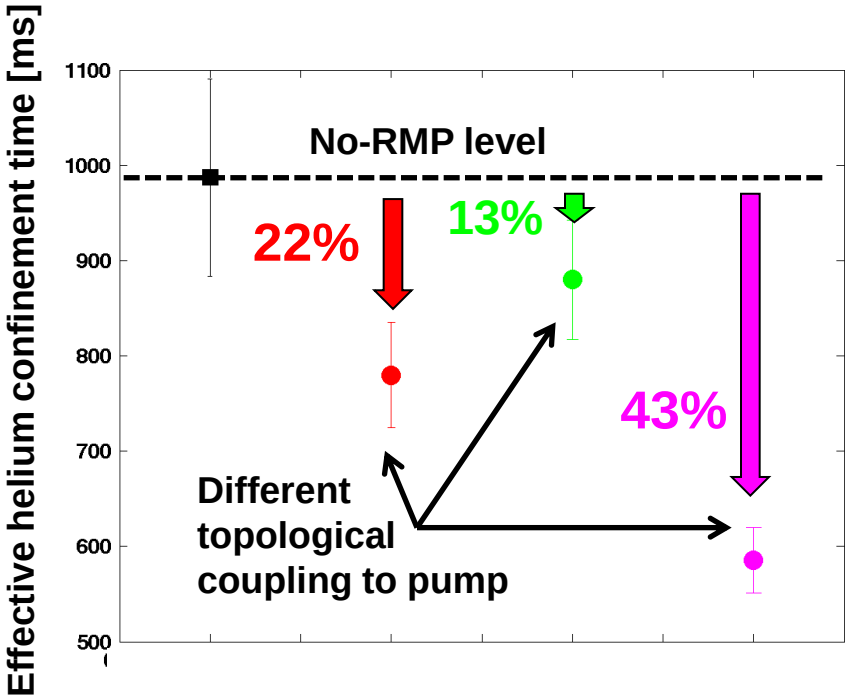


[Schmitz, O.. et al., NF 56 (2016) 106011]

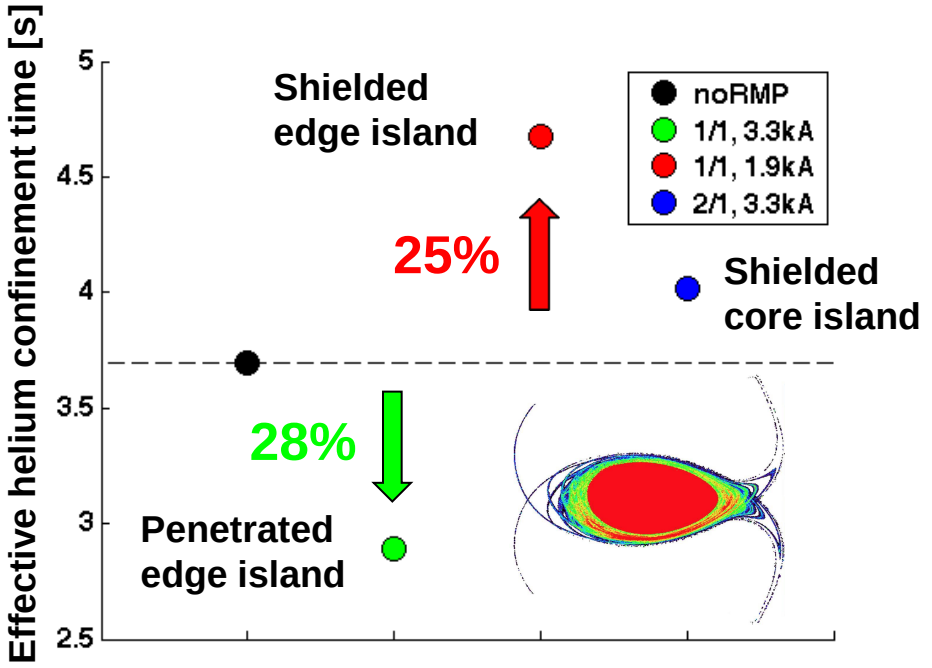
RMP fields were shown at LHD and TEXTOR to be effective in gaining further control on helium exhaust efficiency

25-50% reduction of effective helium confinement time $\tau_p^*{}_{,He}$ by application of resonant magnetic perturbations was seen reliably in the experiment

TEXTOR with Dynamic Ergodic Divertor



LHD with closed helical divertor



- **RMP application is a fine tuning actuator for improvement of divertor functionality**
- **Freedom in 3-D configuration for stellarators offers this optimization intrinsically**